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Frank E. Hoge

GSFC/Wallops Flight Facility/972.0

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A. Task Objective: Algorithm Development for Global Mapping of Phycoerythrin Pigment, Dissolved Organic Matter, and Chlorophyllous Pigment

During prior reporting periods, we described significant advances in the retrieval of inherent optical properties. The algorithm method is a major departure from the radiance ratios used in the old CZCS algorithms. The new method is based on radiance models derived from the radiative transfer equation (RTE). The linear matrix inversion technique is detailed in : Hoge, Frank E. and Paul E. Lyon, "Satellite Retrieval of Inherent Optical Properties by Linear Matrix Inversion of Oceanic Radiance Models: An Analysis of Model and Radiance Measurement Errors", Jour. Geophys. Res. 101, 16,631- 16,648, (1996). This theoretical work has now been extended to include phycoerythrin and phycoerythrobilin absorption coefficients within the matrix inversion. The field test of the radiance inversion algorithm has been conducted and the results recently published: Hoge, F.E., C. Wayne Wright, Paul E. Lyon, Robert N. Swift, James K. Yungel Satellite Retrieval of the Absorption Coefficient of Phytoplankton Phycoerythrin Pigment: Theory and Feasibility Status, Applied Optics **38**, 7431-7441 (1999). The method forms the basis for the ATBD that appears at <http://eospsso.gsfc.nasa.gov/atbd/modistables.html> as ATBD-MOD-27. It has been found by using airborne radiance data that models for total constituent backscatter are pacing items in improving the accuracy of the retrievals. These are of course under intense development within our project. The principal advantage of the matrix inversion method is that it can be extended to include any number of absorbers and backscatterers. Thus it possesses unlimited potential for general algorithm development for retrieval of inherent optical properties and resultant constituent concentrations. The radiative transfer inversion algorithm has recently been applied to SeaWiFS data for MODIS validation test purposes and a manuscript is in press: Frank E. Hoge, C. Wayne Wright, Paul E. Lyon, Robert N. Swift, and James K. Yungel, Inherent optical properties imagery of the western North Atlantic Ocean : I. Horizontal Spatial Variability of the Upper Mixed Layer, Jour. Geophys. Res-Oceans, In-Press, 2000.

B. Additional Task Objective: Airborne Validation of MODIS Ocean Products and Algorithms

The above scientific papers demonstrate that validation is required not only for algorithm development but for the eventual validation of the satellite derived products themselves.

This Additional Task Objective was added during the last reporting period to reflect the added emphasis that the EOS MODIS Team Leader and the MODIS Ocean Team Leader place on validation of ocean products. Validation is defined as the process of establishing the spatial and temporal error fields for a given product or a given algorithm. The validation of MODIS ocean

products and algorithms is a major undertaking that will require strategic use of relatively limited resources. Much of the validation afforded the Coastal Zone Color Scanner (CZCS) was performed from research vessels. The technology associated with instrumentation for moored arrays and airborne platforms had not sufficiently matured during the 1978 - 1986 CZCS data collection period to permit sensors from these platforms to play a more significant validation role. Innovation in remote sensor design and advances in technology during the past decade have led to the development of suitable instrumentation for deployment on moored and aircraft platforms. Some of these sensors have measurement capabilities traditionally associated only with ship platforms and are now capable of significantly complementing the sampling and measurement capability of research vessels for validating certain MODIS ocean color products. For some other MODIS ocean products the remote sensors are not yet sufficiently accurate to provide validation without complementary ship observations. Still other MODIS ocean color products will, for the near future, be dependent almost entirely on ship derived observations.

It has long been recognized that ship, aircraft, and mooring platforms each occupy unique niches in the space/time aspect related to ocean color satellite validation. Moorings can effectively provide a time-series of validation measurements lasting several months, often without attention. Modern moorings are generally equipped to hold a variety of sensors. Current technology often permits the telemetry of measurements through a satellite link such that the moored sensor data is available in essentially real-time. The primary limitation of moored sensors is the restrictive spatial coverage that they afford. Due to the stationary nature of moored platforms, measurements derived from their attached sensors are essentially limited to a single pixel of an ocean color image. Nonetheless, the corroborating measurements from the moored sensor suite can often significantly enhance confidence in ocean color products derived over a considerable portion of a scene. Likewise, repetitive observations in conjunction with satellite overpasses serves to provide assurance in the instrument stability during long time periods when sensors on ship and aircraft platforms are not available.

Airborne sensors have the considerable advantage of being able to acquire contemporaneous measurements that are nearly synoptic over a wide area with corresponding satellite ocean color sensor observations. The spatial extent over which the airborne measurements can be considered sufficiently synoptic for validation purposes is dependent on the physical dynamics of a particular oceanographic province. Nonetheless, since these physical changes are temporal in nature, the spatial coverage afforded by either an aircraft or a ship platform is directly proportional to the speed of the respective platform. Aircraft, such as the NASA P-3B or C-130, routinely cruise at speeds between 130 and 140 m/sec (~250 and ~270 knots), which is approximately 25 - 27 times the speed of a research vessel engaged in along track sampling. Thus, if a 40 km cross-section of ship measurements (acquired during a one hour period surrounding the passage of an ocean color sensor) can be considered sufficiently synoptic for routine validation purposes, then an aircraft similarly engaged could provide a 1,000 km cross-section for direct validation of satellite ocean color products. Often a variety of different sensors can be packaged together and flown on the same aircraft platform to provide a data set of complementary measurements where each individual measurement is enhanced by the presence of the other measurements in the ensemble. The main concern about ocean color product validation from an aircraft platform is in the area of measurement accuracy. As with moored sensors,

considerable improvements have been made to aircraft sensors in recent years such that the measurement accuracy for certain ocean color products is compatible with ship measurements of the same parameter. Still other ocean color products can be measured remotely from an aircraft platform to within acceptable validation standards with the aid of contemporaneous ship observations.

Research vessels are a valuable resource for validating ocean color products. Modern research vessels are capable of housing a variety of instruments, sensors, and laboratory equipment for making a diverse suite of measurements useful for validating ocean color products. Some of these measurements cannot be made from mooring or aircraft platforms. Research vessels are equipped with laboratories for filtering and extracting pigments, have flow through plumbing from which instruments can continuously sample water from the surface layer, can deploy highly technical towed fish (such as the SeaSoar), can carry a variety of optical and biochemical sensors, and are capable of maintaining stations where primary productivity measurements can be conducted. Optical measurements can be made in conjunction with a variety of biogeochemical observations from essentially the same parcel of water. This aspect is particularly valuable in developing models used in the retrieval of ocean color products from MODIS ocean color imagery. Research vessels can collect time-series observations in conjunction with ocean color satellite overpasses, although generally over a shorter time frame than is possible with moored sensor arrays. They also can make measurements over some portion of an ocean color image, although the size of the "near synoptic" sampling region is roughly only 1/25th that of an aircraft platform. It is these temporal and spatial sampling restrictions of a ship platform for validating ocean color products that make the use of mooring and aircraft platforms in concert with some ship sampling essential. In accordance with goals of improving our validation, we frequently place our Shipboard Laser Fluorometer (SLF) aboard cruises of opportunity to obtain high spectral resolution phycoerythrin, chlorophyll, and water Raman scatter data. The SLF has highly successful, with many days of continuous data obtained in 12 hour segments. The PUB induced spectral shift of PEB, when present, is easily seen in the flow-through data without the need for time consuming concentration and/or filtering of samples. SLF data acquisition was conducted on the the cruise of Dr. Patti Matri (Bigelow Laboratories) aboard the RV Hatteras in March of 1998 in the Gulf of Maine, NOAA Estuarine Habitat program in Spring 1998-99 mostly in SAB, and Dennis Clark's MODIS Pre-launch Cruise into the Gulf of California in Oct 1999 and continues through 2000 on other vessels.

This new, additional validation thrust is the result of communication between this MODIS investigator, the MODIS Ocean Discipline Team Leader, and the MODIS Team Leader. It will become a major priority as the need for calibration and validation becomes still more critical. The phycoerythrin effort will be allowed to flow naturally from the principal calibration and validation effort.

In concert with our added emphasis on validation, we have intensified our calibration effort. Prior reports have detailed that Mr. Thomas Riley (GSFC Greenbelt) traveled to Wallops as a part of his world wide calibration round robin. The calibration facility results look quite good for our new reflectance-plaque and standard 200 watt lamp calibration system as now configured in a specially built room-in-a-room calibration facility at Wallops. The calibration sphere, used for many years showed lower precision and will probably not be used for passive radiometric calibration in the future.

1. MODIS North Atlantic Test Site Establishment and Characterization

The Test Site includes the New York Bight/Mid-Atlantic Bight/Gulf Stream/Sargasso Sea and is conveniently located north and east of GSFC/WFF. As previously reported, the MODIS North Atlantic Test Site has been established as originally proposed. Much of the data obtained in the northwestern portion of the test site will be used for algorithm development in Case 2 waters. Characterization has been initiated by ship sampling, aircraft overflights, and analysis of historical data available from within the NASA AOL project since 1980.

It is expected that the MODIS North Atlantic Test Site will be further used for validation of MODIS ocean products and algorithms.

a. During this semiannual reporting period numerous airborne missions were flown within the MODIS MAB Test Site during October 2000. These flights were conducted aboard the NOAA Twin Otter and were part of a cooperative surveys over regions of interest to the NOAA Estuarine Habitat Program. SeaWiFS underflights were also conducted in order to test our ability to validate MODIS products. These missions allow us to refine the techniques to provide validation data for (a) chlorophyll, (b) CDOM, and (c) water-leaving radiances, (d) down-welling irradiance, and (e) sky radiance. Concurrently this data allows further progress on the development of algorithms for chlorophyll and CDOM retrievals. They will also provide additional evaluation of AOL-III and will provide data needed to further calibrate the fluorescence/Raman ratios derived from the AOL spectrometer data to retrieve CDOM and chlorophyll absorption coefficients.

Furthermore, and as previously suggested in a prior report, the above airborne flights allow continued evaluation of a new 256 channel ocean color spectroradiometer designed and built at Wallops Flight Facility. It was found that the color sensor possessed the requisite sensitivity for ocean color spectra in a high-rate/low-integration-time mode needed to allow editing of data containing sun glint. Initially, the prototype sensor was successfully flown during the JGOFS Iron Enrichment Experiments off the coast of Ecuador in November 1993. A still higher sensitivity detector and higher resolution sensor was successfully flown in March 1995 and during the JGOFS Arabian Sea Experiment. Evaluation of the data suggests that it is of good quality.

b. Other Data Acquisition for Algorithm Development/MODIS Validation

New Algorithm Method. As reported in previous reports, a significant advance in the retrieval of inherent optical properties (whose list includes phycoerobilin absorption coefficients and phycoerythrobilin absorption coefficients) was published. The algorithm method is a major departure from the radiance ratios used in the old CZCS algorithms. The new method is based on radiance models derived from the radiative transfer equation (RTE). The linear matrix inversion technique is detailed in : Hoge, Frank E. and Paul E. Lyon, "Satellite Retrieval of Inherent Optical Properties by Linear Matrix Inversion of Oceanic Radiance Models: An Analysis of Model and Radiance Measurement Errors", Jour. Geophys. Res. 101, 16,631- 16,648, (1996). This work

has been extended to phycoerythrin absorption coefficient as described in: Hoge, F.E., C. Wayne Wright, Paul E. Lyon, Robert N. Swift, James K. Yungel Satellite Retrieval of the Absorption Coefficient of Phytoplankton Phycoerythrin Pigment: Theory and Feasibility Status, *Applied Optics* **38**, 7431-7441 (1999). It has been applied to SeaWiFS data as given in Frank E. Hoge, C. Wayne Wright, Paul E. Lyon, Robert N. Swift, and James K. Yungel, Inherent optical properties imagery of the western North Atlantic Ocean : I. Horizontal Spatial Variability of the Upper Mixed Layer, *Jour. Geophys. Res-Oceans*, In-Press, 2001.

These passive retrieval methods, while important for algorithm development, allow us to advance the very techniques that will be used to provide validation for MODIS ocean products.

The RTE inversion method has now been extended to retrieve particulate organic carbon using SeaWiFS data since the MODIS data atmospheric correction is inadequate of inversion algorithms. 2. This coming reporting period will see increased emphasis on validation activities now that TERRA has been launched so our emphasis will in the next reporting period will focus on validation field experiments.

E. Recent Publications

Frank E. Hoge, C. Wayne Wright, Paul E. Lyon, Robert N. Swift, and James K. Yungel, Inherent optical properties imagery of the western North Atlantic Ocean : I. Horizontal Spatial Variability of the Upper Mixed Layer, *Jour. Geophys. Res-Oceans*, In-Press, 2001.

Hoge, F.E., C. Wayne Wright, Paul E. Lyon, Robert N. Swift, James K. Yungel
Satellite Retrieval of the Absorption Coefficient of Phytoplankton Phycoerythrin Pigment: Theory and Feasibility Status, *Applied Optics* **38**, 7431-7441 (1999).

Hoge, Frank E. and Paul E. Lyon, "Spectral Parameters of Inherent Optical Property Models: Feasibility of Satellite Retrieval by Matrix Inversion of an Oceanic Radiance Model", *Applied Optics* **38**, 1657-1662 (1999).

Hoge, Frank E., C. Wayne Wright, Paul E. Lyon, Robert N. Swift, James K. Yungel, Satellite retrieval of inherent optical properties by inversion of an oceanic radiance model: A preliminary algorithm, *Applied Optics* **38**, 495-504 (1999).

Esaias, W., M. Abbott, I. Barton, O. Brown, J. Campbell, K. Carder, D. Clark, R. Evans, F. Hoge, H. Gordon, W. Balch, R. Letelier, P. Minnett, "An Overview of MODIS capabilities for Ocean Science Observations", *IEEE Transactions on Geoscience and Remote Sensing* **36**, 1250- 1265 (1998)

Frank E. Hoge, C. Wayne Wright, Robert N. Swift, and James K. Yungel, Airborne laser-induced oceanic chlorophyll fluorescence: solar-induced quenching corrections by use of concurrent downwelling irradiance measurements, *Applied Optics* 37, 3222-3226 (1998).

Frank E. Hoge, C. Wayne Wright, Todd M. Kana, Robert N. Swift, and James K. Yungel, Spatial variability of oceanic phycoerythrin spectral types derived from airborne laser-induced fluorescence measurements, *Applied Optics* 37, 4744-4749, 1998.

Hoge, Frank E. and Robert N. Swift, Development and validation of satellite retrieval algorithms and derived products: An emerging role for airborne active-passive (laser-solar) ocean color remote sensing, Paper 2964-06, SPIE Special Edition, Volume 2964, 92-99, (1996).

Hoge, Frank E., Robert N. Swift, and James K. Yungel, Oceanic radiance model development and validation: Application of airborne active-passive ocean color spectral measurements, *Applied Optics*, 34, 3468-3476, (1995).

Hoge, Frank E., Anthony Vodacek, Robert N. Swift, James Y. Yungel, Neil V. Blough, Inherent optical properties of the ocean: Retrieval of the absorption coefficient of chromophoric dissolved organic matter from airborne laser spectral fluorescence measurements, *Applied Optics*, 34, 7032-7038, 1995.

F. Other Concerns

The major concern, identified during the last Simi-Annual Reporting period but not explicitly reported, is the lack of adequate atmospheric correction in the ~410nm band and general striping and sun glint problems inherent with Terra-MODIS. Since the PEB retrieval has been demonstrated [see: Hoge, F.E., C. Wayne Wright, Paul E. Lyon, Robert N. Swift, James K. Yungel Satellite Retrieval of the Absorption Coefficient of Phytoplankton Phycoerythrin Pigment: Theory and Feasibility Status, *Applied Optics* **38**, 7431-7441 (1999)], these are the principal reasons that our algorithm is easily applicable to airborne data but not to MODIS data. Intermediate test of our algorithm when applied to SeaWiFS data is therefore now in progress.

The retirement of the NASA/GSFC C-130Q aircraft is still major concern. This leaves only the already-crowded P-3B for major field validation missions. Thus, our size/power/weight/volume reduction to yield AOL-III and use of the NOAA Twin Otter has been a major accomplishment.

As reported previously, the lack of a 600nm band on MODIS-N is no longer felt to be the biggest problem facing the retrieval of the phycoerythrin pigment. Additional effort since the last report still suggest that radiance (and reflectance) models, can provide retrieval of the phycoerythrin pigment at the absorption peaks of 495nm (phycourobilin, PUB) and 545nm (phycoerythrobilin, PEB) can be achieved using the 490nm and 555nm MODIS bands. Of course, such retrievals will require a highly

accurate model to account for the significant amounts of chlorophyll and DOM absorption occurring simultaneously with the phycoerythrin absorptions. The details of the phycoerythrin retrieval have been recently detailed in the ATBD but are being upgraded to linear matrix inversion of a radiance model that includes the phycoerythrobilin and phycourobilin absorption coefficients.